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FOR

METHOD AND APPARATUS FOR INTERLEAVING AND SWITCHING AN OPTICAL
BEAM IN A SEMICONDUCTOR SUBSTRATE

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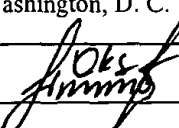
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METHOD AND APPARATUS FOR INTERLEAVING AND SWITCHING AN OPTICAL BEAM IN A SEMICONDUCTOR SUBSTRATE

BACKGROUND OF THE INVENTION

5 Field of the Invention

The present invention relates generally to multiplexing/demultiplexing and switching signals and, more specifically, the present invention relates to multiplexing/demultiplexing and switching optical signals.

Background Information

10 The need for fast and efficient optical switches, multiplexors/demultiplexors, and other similar types of optical devices is increasing as Internet data traffic growth rate is overtaking voice traffic pushing the need for optical communications. Commonly used multiplexors/demultiplexors include diffraction gratings, thin-film filters, fiber Bragg gratings, and arrayed-waveguide gratings. Two commonly found types of optical switches
15 are mechanical switching devices and electro-optic switching devices.

Mechanical switching devices generally involve physical components that are placed in the optical paths between optical fibers. These components are moved to cause switching action. Micro-electronic mechanical systems (MEMS) have recently been used for miniature mechanical switches. MEMS are popular because they are silicon based and are processed
20 using somewhat conventional silicon processing technologies. However, since MEMS technology generally relies upon the actual mechanical movement of physical parts or components, MEMS are generally limited to slower speed optical applications, such as for example applications having response times on the order of milliseconds.

In electro-optic switching devices, voltages are applied to selected parts of a device to
25 create electric fields within the device. The electric fields change the optical properties of

selected materials within the device and the electro-optic effect results in switching action.

Electro-optic devices typically utilize electro-optical materials that combine optical transparency with voltage-variable optical behavior. One typical type of single crystal electro-optical material used in electro-optic switching devices is lithium niobate (LiNbO_3).

5 Lithium niobate is a transparent, material that exhibits electro-optic properties such as the Pockels effect. The Pockels effect is the optical phenomenon in which the refractive index of a medium, such as lithium niobate, varies with an applied electric field. The varied refractive index of the lithium niobate may be used to provide switching. The applied electrical field is provided to present day electro-optical switches by external control
10 circuitry.

Although the switching speeds of these types of devices are very fast, for example on the order of nanoseconds, one disadvantage with present day electro-optic switching devices is that these devices generally require relatively high voltages in order to switch optical beams. Consequently, the external circuits utilized to control present day electro-optical
15 switches are usually specially fabricated to generate the high voltages and suffer from large amounts of power consumption. In addition, integration of these external high voltage control circuits with present day electro-optical switches is becoming an increasingly challenging task as device dimensions continue to scale down and circuit densities continue to increase.

BRIEF DESCRIPTION OF THE DRAWINGS

The present invention is illustrated by way of example and not limitation in the accompanying figures.

Figure 1 is a block diagram illustrating one embodiment of an optical interleaver in accordance with the teachings of the present invention.

Figure 2 is a block diagram illustrating another embodiment of an optical interleaver including switching capability in accordance with the teachings of the present invention.

Figure 3 is a cross-section diagram of one embodiment of a multi-mode interference (MMI) coupling device in accordance with the teachings of the present invention.

Figure 4 is an illustration operation of one embodiment of an MMI coupling device in accordance with the teachings of the present invention.

Figure 5 is a block diagram illustrating one embodiment of cascaded or stacked optical interleavers in accordance with the teachings of the present invention.

Figure 6 is a block diagram illustrating another one embodiment of cascaded or stacked optical interleavers including switching capability in accordance with the teachings of the present invention.

DETAILED DESCRIPTION

Methods and apparatuses for switching optical beams in a semiconductor substrate are disclosed. In the following description numerous specific details are set forth in order to provide a thorough understanding of the present invention. It will be apparent, however, to one having ordinary skill in the art that the specific detail need not be employed to practice the present invention. In other instances, well-known materials or methods have not been described in detail in order to avoid obscuring the present invention.

Reference throughout this specification to “one embodiment” or “an embodiment” means that a particular feature, structure or characteristic described in connection with the embodiment is included in at least one embodiment of the present invention. Thus, appearances of the phrases “in one embodiment” or “in an embodiment” in various places throughout this specification are not necessarily all referring to the same embodiment. Furthermore, the particular features, structures or characteristics may be combined in any suitable manner in one or more embodiments.

In one embodiment of the present invention, a semiconductor-based optical interleaver is provided in a fully integrated solution on a single integrated circuit chip. Various embodiments of the optical interleaver in accordance with the teachings of the present invention include an optical splitter disposed in a semiconductor substrate at least one input and two outputs. Accordingly, an optical beam received at one of the inputs of the optical splitter is split into two beams with substantially equal amplitude and almost $\pi/2$ phase shift. Conversely, two optical beams received at the outputs of the splitter with $-\pi/2$ phase difference are output as a combined beam from the input of the optical splitter. In one embodiment, this optical splitter includes a multi-mode interference (MMI) coupling device including two inputs and two outputs. When this MMI coupling device is used as an optical

splitter, one of the two inputs of the MMI coupling device is coupled to receive the optical beam and the split optical beams are output from the two outputs of the MMI coupling device.

In one embodiment, the two split beams output from the outputs of the above-described optical splitter are coupled to two inputs of another MMI coupling device through an unbalanced pair of optical couplers. In one embodiment, the unbalanced pair of optical couplers includes two waveguides in the semiconductor substrate having different optical path lengths. The MMI coupling device receiving the split optical beams through the unbalanced pair of optical couplers includes two outputs. In one embodiment, the two outputs of this MMI coupling device output optical beams dependent on the wavelength or frequency components of the optical beams. Accordingly, an optical beam having one wavelength or subset of wavelengths is output from one of the outputs of the MMI coupling device in accordance with the teachings of the present invention. Another optical beam having a different wavelength or a different subset of wavelengths is output from the other output of the MMI coupling device in accordance with the teachings of the present invention.

In one embodiment, it is appreciated that optical beams may propagate in either direction through the above-described optical interleaver. Accordingly, an optical interleaver in accordance with the teachings of the present invention may function as a multichannel optical multiplexor and/or an optical demultiplexor. In addition, a plurality of optical interleavers in accordance with the teachings of the present invention may be cascaded or stacked together to provide multiplexors or demultiplexors with various configurations having multiple inputs or outputs. In one embodiment, optical switches may be optically coupled to the inputs and/or outputs of an interleaver to selectively switch or couple optical beams having different wavelengths to different optical ports in accordance with the

teachings of the present invention. Embodiments of the disclosed optical interleaving and switching devices can be used in a variety of high bandwidth applications including multi-processor, telecommunications, networking or the like. In addition, embodiments of the disclosed optical interleaving devices may be used for reconfigurable add/drop systems.

5 To illustrate, Figure 1 is a block diagram illustrating one embodiment of an optical interleaver 101 disposed in a semiconductor substrate 117 in accordance with the teachings of the present invention. In one embodiment, semiconductor substrate 117 includes silicon, a III-V semiconductor material or the like. As shown in the depicted embodiment, an optical splitter 103 is optically coupled to receive an optical beam 111 at an input of the optical
 10 splitter 103. In one embodiment, optical beam 111 is a multichannel optical beam carrying a plurality of channels, each of which having different wavelengths such as for example λ_1 , λ_2 , λ_3 and λ_4 . It is noted that four wavelengths λ_1 , λ_2 , λ_3 and λ_4 are shown in Figure 1 for explanation purposes. It is appreciated that optical beam 111 may include a greater or fewer number of wavelengths in accordance with the teachings of the present invention. In one
 15 embodiment, the multiple wavelengths included in optical beam 111 correspond to infrared or near-infrared wavelengths. In one embodiment, the multiple wavelengths included in optical beam 111 correspond to substantially equal frequency-spaced (e.g. 100 GHz) signals having wavelengths approximately equal to 1.3 μm or 1.55 μm or the like.

As shown in the depicted embodiment, optical splitter 103 includes two outputs from
 20 which split versions of optical beam 111 are output. In one embodiment, optical splitter 103 is a multi-mode interference (MMI) coupling device having two inputs and two outputs. In the embodiment depicted in Figure 1, one of the two inputs of the MMI coupling device used to form optical splitter 103 is coupled to receive optical beam 111. It is appreciated that although the terms “input” and “output” have been used herein for explanation purposes the

direction of propagation of the optical beam 111 may be reversed in accordance with the teachings of the present invention. Accordingly, in an embodiment in which optical beam 111 is propagating in the opposite direction, optical beam 111 is generated at the input of optical splitter 103.

5 As shown in Figure 1, one embodiment of optical interleaver 101 also includes an MMI coupling device 105 disposed in semiconductor substrate 117 and having two inputs and two outputs. The two inputs of MMI coupling device 105 are optically coupled to receive the two split versions of optical beam 111 through an unbalanced pair of optical couplers 107 and 109. In one embodiment, optical couplers are optical waveguides disposed
10 in semiconductor substrate 117 having different optical path lengths. In one embodiment, the optical waveguides used to form optical couplers 107 and 109 are formed with silicon waveguides with oxide cladding disposed in semiconductor substrate 117. In one embodiment, the optical waveguides used to form optical couplers 107 and 109 include rib waveguides disposed in a silicon on insulator (SOI) wafer. As shown in Figure 1, the optical
15 path lengths of optical couplers 107 and 109 differ by ΔL in one embodiment.

In one embodiment, since optical couplers 107 and 109 have optical path lengths that differ by ΔL , the outputs from MMI coupling device 105 show an interference pattern in the optical frequency domain and the output spectrum at one of the outputs of MMI coupling device 105 is described by the following equation:

$$20 \quad I_1(\nu) = I_i(\nu) \cos^2(\nu n \Delta L \pi / c), \quad (\text{Equation 1})$$

where ν is the optical frequency, n is the effective index of refraction of the guided mode in the optical coupler and c is the speed of light in a vacuum. The output spectrum at the other output of MMI coupling device 105 is given by:

$$I_2(\nu) = I_1(\nu) \sin^2(\nu n \Delta L \pi / c). \quad (\text{Equation 2})$$

Thus, when multi-channel optical beam such as optical beam 111, which in the illustrated example includes wavelengths $\lambda_1, \lambda_2, \dots \lambda_N$, is coupled into the input of optical splitter 103, the two outputs of MMI coupling device 105 have wavelength components of $\lambda_1, \lambda_3, \dots \lambda_{N-1}$ and $\lambda_2, \lambda_4, \dots \lambda_N$, respectively, as shown in Figure 1. The channel spacing, $\Delta\nu$, is related to the optical path difference ΔL by

$$\Delta\nu = c/(2n\Delta L). \quad (\text{Equation 3})$$

In an example embodiment for a 100 GHz optical interleaver 101, the optical path difference ΔL is about 435 μm between optical couplers 107 and 109. It is appreciated that the channel spacing of the interleaver is also determined by the effective index of the waveguide mode. Therefore, changing the waveguide dimension as well as the temperature leads to a change in the channel spacing.

In one embodiment, optical interleaver 101 is used to separate one set substantially equal frequency-spaced (e.g. 100 GHz) signals of a multichannel optical signal into two subsets of signals with double frequency-spacing (e.g. 200 GHz) between the channels. As also shown in the embodiment depicted in Figure 1, light may also propagate in the opposite direction such that optical interleaver 101 multiplexes or combines the double frequency-spaced channels received at the two outputs of MMI coupling device 105 into an equal frequency-spaced multichannel signal, which is output from the input of optical splitter 103.

Figure 2 is an illustration of another embodiment of an optical interleaver 201 including switching capability in accordance with the teachings of the present invention. As shown in the illustrated embodiment, optical interleaver 201 is similar to optical interleaver 101 as an optical splitter 103 is included to split a multichannel equal frequency-spaced

optical beam 111 into two split beams. The split beams of optical beam 111 are optically coupled to be received by an MMI coupling device 105 through an unbalanced pair of optical couplers 107 and 109 such that optical beams 113 and 115 are output from the two outputs of MMI coupling device 105.

5 As shown in the embodiment depicted in Figure 2, an optical switch 203 disposed in semiconductor substrate 117 is also included in interleaver 201. In one embodiment, optical switch 203 is an N x N optical such as for example a 2 x 2 optical switch having two inputs and two outputs. In one embodiment, each of the two outputs of optical switch 203 is selectively optically coupled to either of the two inputs of optical switch 203 in response to a control signal 205. In operation, the first input of optical switch 203 may be selectively optically coupled to the first output or the second output of optical switch 203. Similarly, the second input of optical switch 203 may be selectively optically coupled to the first output or the second output of optical switch 203. Accordingly, channels of optical beam 111 can be switched to individual output ports with optical switch 203 in accordance with the teachings of the present invention.

Thus, in the example embodiment illustrated in Figure 2, optical beam 115 including wavelengths λ_2 and λ_4 is output at a first one of the outputs of optical switch 203 and optical beam 113 including wavelengths λ_1 and λ_3 is output at a second one of the outputs of optical switch 203 in response to control signal 205. It is appreciated that control signal 205 can be used to switch the outputs of optical switch 203 such that optical beam 115 is output at the second one of the outputs of optical switch 203 and optical beam 113 is output at the first one of the outputs of optical switch 203.

In another embodiment, it is appreciated that optical switch 203 may be optically coupled to the inputs of optical splitter 103. In such an embodiment, an MMI coupling

device having two inputs and two outputs, similar to for example MMI coupling device 105 may be utilized as optical splitter 103.

It is noted that various embodiments of optical switches that may be employed as optical switch 203 are described in co-pending application serial no. _____, filed _____, entitled "Method and Apparatus for Switching an Optical Beam in a Semiconductor Substrate," and assigned to the Assignee of the present application.

Figure 3 is a cross-section diagram of one embodiment of an MMI coupling 305 device in accordance with the teachings of the present invention. In one embodiment, MMI coupling device 305 is disposed in a semiconductor substrate 305. In one embodiment, a semiconductor waveguide 325 is defined in semiconductor substrate 305 between lateral insulating regions 327 and between a buried insulating layer 321 and insulating region 323 of a silicon on insulator (SOI) wafer. Buried insulating layer 321 is disposed between semiconductor substrate 317 and semiconductor substrate 319 of the SOI wafer. In one embodiment, insulating region 323 includes an interlayer dielectric layer of the SOI wafer. In one embodiment, insulating regions 323, 327 and buried insulating layer 321 include an oxide material or the like, which form cladding for waveguide 317. The cladding provided by insulating regions 323, 327 and buried insulating layer 321 confine an optical beam propagating through waveguide 325 to remain within waveguide 325 as a result of total internal reflection since oxide has a smaller index of refraction than the semiconductor material of waveguide 325.

Figure 4 is an illustration operation of one embodiment of a portion of an MMI coupling device 407 in accordance with the teachings of the present invention. In one embodiment, MMI coupling device 407 may be used in place of MMI coupling device 105 or optical splitter 103 in accordance with the teachings of the present invention. As shown,

MMI device 407 includes a waveguide 438 disposed in a semiconductor substrate 443. In one embodiment, an optical beam 435 is directed into waveguide 438 through an input 409. In one embodiment, optical beam 435 is confined to remain within waveguide 438 with cladding 420 until exiting. As shown, the cladding 420 enclosing waveguide 438 in one embodiment has a length L and a width W and is designed to support a large number of modes in waveguide 438. In one embodiment, there are two outputs from waveguide 438 shown as waveguides outputs 413 and 415.

As illustrated in Figure 4, optical beam 435 propagates from input 409 into waveguide 438 and is eventually deflected from the cladding 420 enclosing waveguide 438. The deflected wavefronts of optical beam 435 interfere with each other within waveguide 438 of MMI coupling device 407 such that maximas 440 and minimas 442 are created as shown. In one embodiment, L and W are designed such that there is a maxima 440 located at each output location corresponding to the outputs 413 and 415. Thus, the two outputs 413 and 415 of MMI coupling device 407 are optically coupled to the input 409 of coupling MMI device 407. In one embodiment, split optical beams 435 output from outputs 413 and 415 have substantially equal amplitude and almost $\pi/2$ phase shift. Accordingly, MMI coupling device 407 functions as a 3dB beam splitter and splits optical beam 435 into two beams with substantially equal amplitude.

It is appreciated that MMI device 407 has been illustrated for clarity including one input 409. However, it is appreciated that another input (not shown) is included and that an optical beam input to the second input is also split and output at outputs 413 and 415 as described above. In addition, it is appreciated that the direction of propagation of the optical beams may be reversed in accordance with the teachings of the present invention.

Figure 5 is a block diagram illustrating one embodiment of stacked or cascaded

optical interleavers 501 in accordance with the teachings of the present invention. As shown in the depicted embodiment, optical interleavers 101, 503 and 505 are disposed in semiconductor substrate 117. In one embodiment, optical interleavers 503 and 505 include substantially similar structures to those included in optical interleaver 101 and described above. As shown, a first output of optical interleaver 101 is optically coupled to an input of interleaver 503 and a second output of optical interleaver 101 is optically coupled to an input of interleaver 505.

In operation, an optical beam 111 is optically coupled to be received at an input of optical interleaver 101. In one embodiment, optical beam 111 is a multichannel optical beam carrying a plurality of channels, each of which having different wavelengths such as for example λ_1 , λ_2 , λ_3 and λ_4 . In one embodiment, the multiple wavelengths included in optical beam 111 correspond to substantially equal frequency-spaced signals. As shown in the depicted embodiment, double frequency-spaced optical beams 113 and 115 are output from the two outputs of optical interleaver 101. Accordingly, optical beams 113 and 115 have wavelength components of $\lambda_1, \lambda_3, \dots, \lambda_{N-1}$ and $\lambda_2, \lambda_4, \dots, \lambda_N$, respectively, as shown in Figure 5. By cascading optical interleavers 503 and 505 to the outputs to the optical interleaver 101, optical beam 111 is further demultiplexed such that the two outputs of optical interleaver 503 have single channel wavelength components λ_1 and λ_3 , respectively, and the two outputs of optical interleaver 505 have single channel wavelength components λ_2 and λ_4 , respectively.

Thus, the embodiment illustrated in Figure 5 shows a 4 channel multiplexor/demultiplexor employing 3 cascaded interleavers 101, 503 and 505 in accordance with the teachings of the present invention. It is appreciated that additional channels may be multiplexed and/or demultiplexed by cascading additional interleavers in accordance with the teachings of the present invention.

Figure 6 is a block diagram illustrating another one embodiment of cascaded or stacked optical interleavers 601 including switching capability in accordance with the teachings of the present invention. As shown in the illustrated embodiment, cascaded optical interleavers 601 is similar to cascaded optical interleavers 501 as the two outputs of optical interleaver 101 are optically coupled to inputs of optical interleavers 503 and 505.

As shown in the embodiment depicted in Figure 6, optical switches 603, 607 and 611 disposed in semiconductor substrate 117 are optically coupled to optical interleavers 101, 503 and 505, respectively. In one embodiment, optical switches 603, 607 and 611 are 2 x 2 optical switches having two inputs and two outputs each. In one embodiment, each of the two outputs of optical switches 603, 607 and 611 are selectively optically coupled to either of the two inputs of optical switches 603, 607 and 611 in response to a control signals 605, 609 and 613, respectively.

In operation, multichannel optical beam 111 having wavelengths such as for example λ_1 , λ_2 , λ_3 and λ_4 is received by interleaver 101. Optical beam 113 having wavelengths λ_1 and λ_3 is selectively output at either one of the two outputs of optical interleaver 101 and optical beam 115 having wavelengths λ_2 and λ_4 is selectively output at either one of the two outputs of optical interleaver 101. Accordingly, optical interleaver 503 is selectively optically coupled to receive optical beam 113 or 115 from optical interleaver 101 in response to control signal 605. Similarly, optical interleaver 505 is also selectively coupled to receive optical beam 113 or 115 from optical interleaver 101 in response to control signal 605.

Assuming optical interleaver 503 is optically coupled to receive optical beam 113, optical beam 507 having wavelength λ_1 is output at one of the two outputs of optical interleaver 503 and optical beam 509 having wavelength λ_3 is output at the other output of

optical interleaver 503. Using optical switch 607, optical beams 507 and 509 can be selectively optically coupled between two different output ports in accordance with the teachings of the present invention.

Assuming optical interleaver 503 is optically coupled to receive optical beam 113,
 5 optical beam 507 having wavelength λ_1 is output at one of the two outputs of optical interleaver 503 and optical beam 509 having wavelength λ_3 is output at the other output of optical interleaver 503. Using optical switch 607, optical beams 507 and 509 can be selectively optically coupled between two different output ports in response to control signal 609 in accordance with the teachings of the present invention. Thus, in the example
 10 embodiment illustrated in Figure 6, optical beam 509 including wavelength λ_3 is output at a first one of the outputs of optical switch 607 and optical beam 507 including wavelength λ_1 is output at a second one of the outputs of optical switch 607 in response to control signal 607. It is appreciated that control signal 607 can be used to switch the outputs of optical switch 607 such that optical beam 509 is output at the second one of the outputs of optical switch
 15 607 and optical beam 507 is output at the first one of the outputs of optical switch 607.

Assuming optical interleaver 505 is optically coupled to receive optical beam 115,
 optical beam 511 having wavelength λ_2 is output at one of the two outputs of optical interleaver 505 and optical beam 513 having wavelength λ_4 is output at the other output of optical interleaver 505. Using optical switch 611, optical beams 511 and 513 can be
 20 selectively optically coupled between two different output ports in response to control signal 613 in accordance with the teachings of the present invention. Thus, in the example embodiment illustrated in Figure 6, optical beam 513 including wavelength λ_4 is output at a first one of the outputs of optical switch 611 and optical beam 511 including wavelength λ_2 is

output at a second one of the outputs of optical switch 611 in response to control signal 613.

It is appreciated that control signal 613 can be used to switch the outputs of optical switch 611 such that optical beam 513 is output at the second one of the outputs of optical switch 611 and optical beam 511 is output at the first one of the outputs of optical switch 611.

- 5 In the foregoing detailed description, the method and apparatus of the present invention have been described with reference to specific exemplary embodiments thereof. It will, however, be evident that various modifications and changes may be made thereto without departing from the broader spirit and scope of the present invention. The present specification and figures are accordingly to be regarded as illustrative rather than restrictive.

FIG. 1 is a block diagram of an optical switch 611 in accordance with the present invention. The optical switch 611 includes a control input 613, a first output 511, and a second output 513. The control input 613 is connected to a control circuit 615, which is connected to a switch 617. The switch 617 is connected to the first output 511 and the second output 513. The control circuit 615 is configured to receive a control signal 613 and to output a control signal 615 to the switch 617. The switch 617 is configured to switch the first output 511 and the second output 513 in response to the control signal 615.